A HIGH FREQUENCY RESONANT SCANNER USING THERMAL ACTUATION

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ABSTRACT

Large deflection MEMS scanning mirrors are sometimes difficult to design as they require large clearances to avoid collisions. This paper describes a surface micromachined thermally actuated 1D optical scanner capable of large deflection. An array of in-plane Joule heated buckle beams is configured to produce a torque that rotates a cantilevered mirror away from the substrate. The high-Q structure enables deflection of the mirror through large scan angles when operated at resonance. The RMS heating of the buckle beams at high frequencies coupled with residual stress in the mirror's cantilever lift the mirror away from the substrate to help avoid collisions during operation.

INTRODUCTION

Micromirrors with linear deflection behaviors have been found useful for systems requiring 1D and 2D optical scanning patterns such as for bar code and 2D imaging applications. Micromachined scanning mirrors with large angle deflections requiring equally large operating clearances have been relegated mostly to 3D structures erected out of plane [1,2] or through deep cavity etching [3] or special packaging. Many of those erected out of plane need either manual erecting efforts or a special actuator mechanism to effect the same. Also, out-of-plane erecting generally requires the use of friction-plagued hinges or similar structures to articulate the rigid 2D planar structures into their final 3D form. The device described in this paper differs from most mirror scanners in that a torque and not a linear force is used to vibrate a cantilevered mirror structure at resonance. Frequencies as high as 18KHz with deflections above 20 optical degrees have been observed.

ACTUATOR DESIGN

The fabrication process used to build the scanner is Cronos' MUMPs (multi-user MEMS processes) [3]. The MUMPs process offers three structural polysilicon layers of which two are released. The layers are fabricated on the substrate over a 0.5um layer of insulating silicon nitride. Poly0, 1 and 2 structural layer are 0.5µm, 2.0µm and 1.5µm thick with Poly0 nearest the nitride. A 0.5µm layer of gold can be patterned on top of the Poly2. Figure 1 shows a cross section diagram of the basic buckle beam actuator used for mirror deflection.

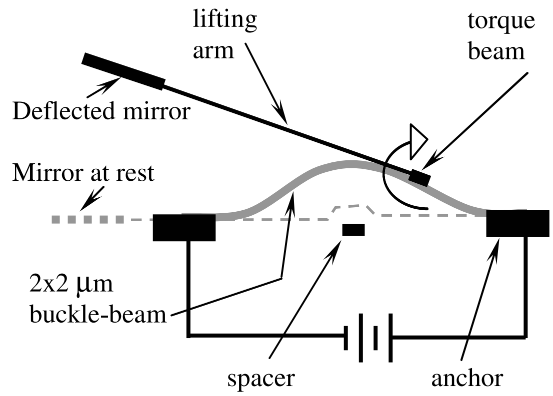

Figure 1: Basic buckle beam actuator.

A 2.0µm x 2.0µm clamp-clamp Poly1 cantilever is Joule heated causing it to expand due to a positive TCE (thermal coefficient of expansion) and buckles out-of-plane. Typically there is no affinity for a straight beam to buckle in any preferred direction. A small asymmetry is introduced in the beam design to enable the beams to buckle only out-of-plane. A 0.5µm Poly0 spacer placed under the beam which creates a conformal hump at the center producing a small elevation at the point of maximum bending. The result is an out-of-plane buckle preference.

The maximum derivatives of beam deflection occur at points 25% of the beam's length from either anchor. At one of these locations of maximum derivative, a cross beam is added to take advantage of the torque produced there. A number of buckle beams are arranged in parallel for increased torque. A two degree of freedom non-resonant scanner has been built using this method [4] and demonstrated as a laser vector display. The ends of the torque beam are connected to a pair of flexible lifting arms with a mirror attached at the opposite end. Figure 2 is a plan and cross-section diagram of a working scanner. Note the conformal hump at the center of the buckle beams.

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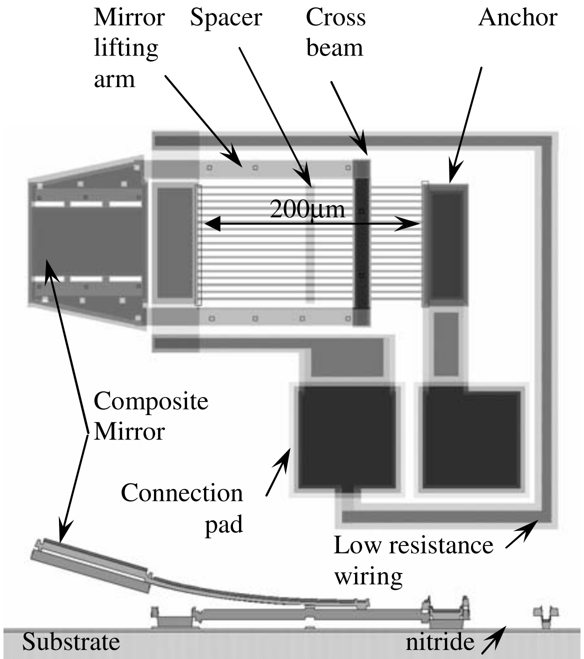

Figure 2. Plan and cross-section CAD diagram of the resonant mirror.

The high modulus of the polysilicon beams and lifting arms coupled with the mass of the mirror produce a structure with a high Q for out-of-plane movement. Preliminary tests indicated high frequency resonant structures with large deflections were possible. A problem occurs at resonance however, where the mirror physically collides with the nitride layer causing a reduction and nonlinearity in the output the resonance. This is probably due to squeeze-damping phenomena between the mirror and the substrate at close separations. Adding a DC offset to the excitation current lifted the mirror slightly but still hindered the maximum deflection possible and limited the peak to peak current and scan angle.

A common fate of the MEMS designer is residual stress caused by uneven thermal expansion of dissimilar materials layered at fabrication and subsequently released. This consequence can warp a released polysilicon-metal structure and is generally undesired. This is commonly observed in MUMPs Poly2 structures coated with gold, especially in mirrors larger than around 50µm on a side. The 60µm x 92µm mirror shown in Figure 2 is a composite of Poly1, Oxide2 and Poly2 layers with gold deposited on the Poly2 for the mirror. Figure 3 shows this in cross section. The Poly1 and Poly2 layers are sealed at the mirror's edge with no intervening etch holes, thus trapping the Oxide2 layer. This composite structure is rigid enough to resist most of the residual stress forces, resulting in a reasonably flat mirror. The final HF etch provided

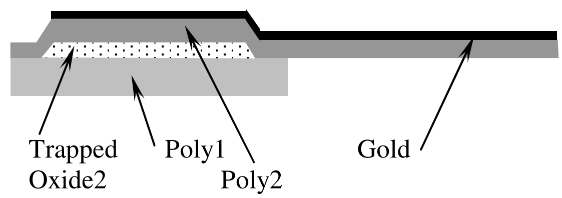

Figure 3. Cross-section of a mirror showing the stiffened composite structure designed to resist warping from residual stress.

by Cronos was sufficient to release the 60µm x 92µm mirror even though the MUMPs design rules recommend a 30µm maximum distance between etch holes. The non-square aspect ratio of the mirror was chosen so that an illuminating laser would stay within the mirror's field of view during large deflections.

A gold layer is also added to the 1.5µm thick Poly2 lifting arms but in this case, allowing the residual stress to curl them upward, away from the substrate as shown in Figure 2. This post-release warping achieves about a 4.5 degree out-of-plane bias to the mirror's idle position, reducing the chance for mirror-to-substrate collision during large angle deflections. Figure 4 is a photomicrograph of an operational scanner.

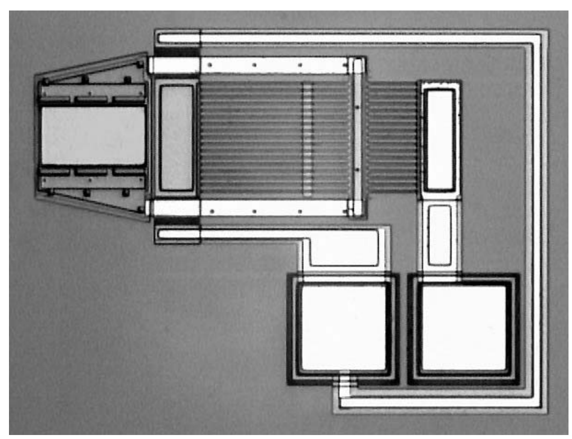

Figure 4. Photomicrograph of a working scanner.

SCANNER OPERATION AND RESULTS

An advantage of thermal actuation over electrostatic is the low voltages typically required. The scanner actuators are designed to operate from logic levels. The terminal voltage iss maintained below 5 volts to keep from overheating the buckle beams and possibly damaging the device. A 4.5 volt peak excitation is calculated to cause the thermal buckle beams to heat to a maximum of around 600 to 700 deg C, below the permanent deformation limit. To test the devices, the square wave output of a signal generator is fed into a general purpose amplifier which in turn is connected to a Signatone S-250 probe station to test the MUMPs die. Peak current observed at 4.5 volt excitation is 36 ma. A Helium Neon laser, aimed 45 degrees off the substrate normal and coplanar with the center buckle beam, is focused on the mirror. The mirror reflection illuminates a calibrated target screen one meter away. The laser spot size on the MEMS device is allowed to spill over the mirror onto the nitride layer. This causes an additional spot on the target screen indicating the relative angle of the substrate with respect to the mirror deflection. This establishes the zero-degree (substrate) reference.

The static deflection response as a function of the applied voltage is shown in Figure 5. A near-linear

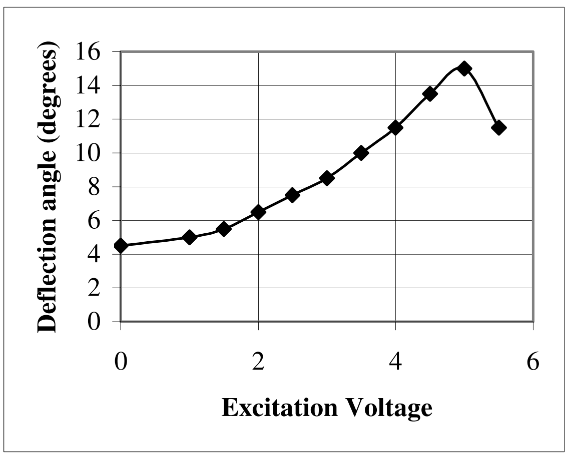

Figure 5. Static deflection behavior of a thermally actuated 1D scanning mirror.

behavior is observed between 1 and 4.5 volts. No attempt is made to further linearize the function as the scanner is designed to operate at resonance where the time response is close to sinusoidal. Note the 4.5 degree angle with respect to the substrate at zero excitation volts. This is a result of the desired residual stress warping in the mirror cantilever arms. In the figure, the non-monotonic behavior above a 5 volt excitation is the result of a permanent deformation of the buckle beams and should be avoided during normal operation. A maximum not-to-exceed RMS voltage (heating value) should be calculated according to scanner usage to avoid destroying or permanently deforming the device. Figure 6 shows the upper and lower angular deflection limits of this particular scanner device as a function of frequency. The device is excited with a 4 volt square wave for this experiment. The half-amplitude bandwidth is around 1 KHz. The resonance is around 8 KHz with a maximum total mirror excursion of 18 optical degrees. Note that at frequencies above resonance, the mirror is unable to mechanically respond to the rapid heating and cooling of the buckle beams. In this situation the mirror assumes a static deflection value equal to the residual stress offset of 4.5 degrees plus the deflection due to the signal's RMS heating

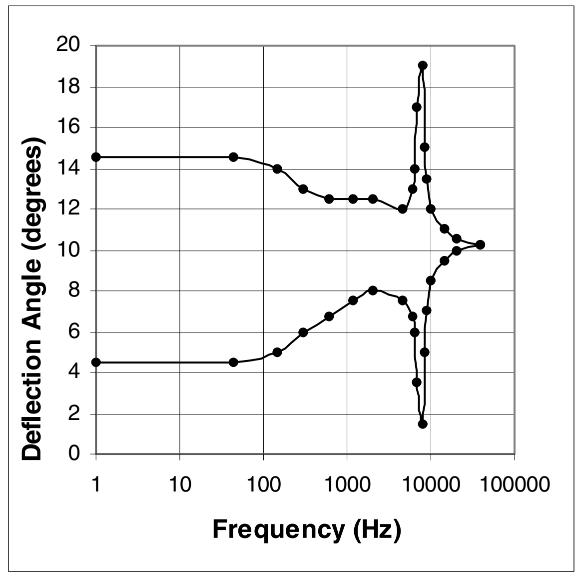

Figure 6. Frequency response of the scanner's upper and lower deflection limits.

value of 2 volts for a total of a 10 degree offset. These biases due to the residual stress and average heating value of the signal contribute to elevating the mirror above and avoiding collision with the substrate.

CONCLUSION

A thermally actuated high frequency large angle mirror deflection should help dispel the notion that thermal actuators are relegated to applications requiring only high force or low speed. The 160mw power consumption however is considerable for a MEMS device so these techniques should be used sparingly. The constructive use of residual stress and RMS signal value at high frequencies produces a mechanical offset to the mirror so that a 3D structure or a deep cavity below the mirror is unnecessary.

Future work is proposed to integrate a resonant structure similar to the one described here into one axis of a 2D scanner [4] to be used as a video raster generator. A concept of this device is shown in Figure 7. Another 2D scanner is proposed by

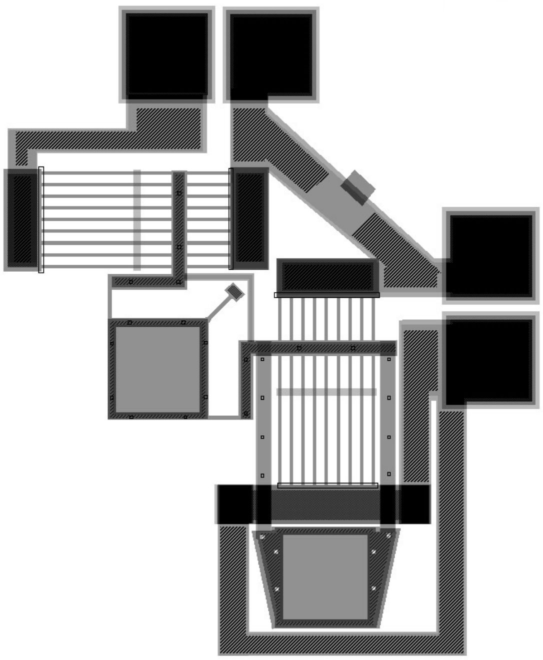

Figure 7. Proposed 2D raster scanner.

designing two 1D scanners and an optical beam folding mechanism. One of the 1D scanners will be similar to the one described in this paper and the other a slower linearized one. This is also being designed to produce a video raster.

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